FED-Vol. 153, Cavitation and Multiphase Flow
ASME 1993

THE MICRO-BUBBLE DISTRIBUTION IN THE WAKE OF A CAVITATING CIRCULAR CYLINDER

K. Sato, Zhenhuan Liu, and C. E. Brennen
California Institute of Technology
Pasadena, California

ABSTRACT

Bubble nuclei populations in the wake of a circular cylinder under cavitating and noncavitating conditions were measured using a Phase Doppler Anemometry (PDA) system. In addition, the mean velocity defect and the turbulent fluctuations were monitored in order to try to understand the nuclei population dynamics within the flow. At the Reynolds numbers of these experiments ($20000 \rightarrow 33000$) the laminar near-wake is fairly steady and under very limited cavitation conditions nuclei accumulate in this wake so that the population there is several orders of magnitude larger than in the upstream flow. Further downstream the population declines again as nuclei are entrained into the wake. However at fifteen diameters downstream the population is still much larger than in the upstream flow.

1. INTRODUCTION

Ever since the watershed experiments of Lindgren and Johnsson (1966) it has been widely accepted that cavitation inception and patterns of flow are dependent on the population of micron-sized "cavitation nuclei" present in the flow. Yet progress toward establishing the relationship between these nuclei and the cavitation they produce has been relatively slow, in part because of the difficulties in measuring the nuclei population in a water tunnel environment. The pioneering efforts of Keller (1972, 1974) in developing optical scattering methods have been followed by other valuable contributions (for example, Ahamed and Hammitt (1975), Gates and Bacon (1978), Peterson et al. (1975), O'Hern et al. (1988)). Yet as Billet (1985) has indicated in his review, perhaps the only reliable methods of obtaining the nuclei number density distribution function (defined as $N(R)$ where $N(R)dR$ is the number of nuclei per unit sample volume with radii between R and $R + dR$) are the holographic methods in which the nuclei present in a reconstructed hologram are directly counted. The difficulty with this approach is that it is laborious and time-consuming and does not permit on-line monitoring of the changes in the water tunnel nuclei population during an experiment.

In our laboratory, Liu (1992) has cooperated jointly with Dantec in developing and calibrating a light-scattering instrument for nuclei population measurement. These results and the investigation of nuclei population dynamics will be reported later. The present paper presents the results of an investigation into the variation of the nuclei population within a typical flow and we have chosen to examine the classic case of flow around a circular cylinder. The motivation is to gain some understanding of how the nuclei population varies from one location to another within such a flow since the cavitation inception and flow pattern may well depend on the details of that distribution. Of course, the nuclei are sufficiently small that most are simply convected along as would be particles of fluid. But it is also possible for nuclei to accumulate in a wake, in a separation bubble or, perhaps, in a vortex and such concentrations may have important consequences. Kato (1985) has also demonstrated that cavitation itself supplies nuclei to the water tunnel population: he also used a PDA instrument to show that the population downstream of a cavitating foil was about two orders of magnitude larger than the population density upstream. In this paper we simultaneously measure the velocity, the turbulent fluctuations and the nuclei population in the wake of a circular cylinder in order to provide some evidence of nuclei population dynamics.

2. EXPERIMENT

The experiments were conducted in the Caltech Low Turbulence Water Tunnel (LTWT), shown in Figure 1. A full descrip-

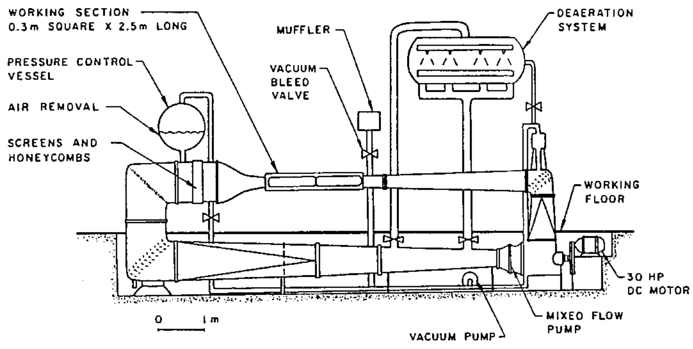

Figure 1 Diagram of the Low Turbulence Water Tunnel (LTWT) (not to scale).

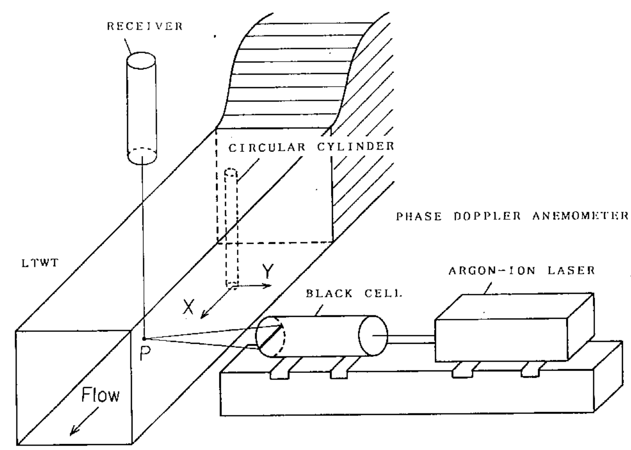

Figure 2 Schematic diagram of Phase Doppler Anemometry (PDA) system.

tion of the tunnel, which has a 31 [cm] × 31 [cm] working section, is presented by Gates (1977). A circular cylinder with a diameter, D , of 6.35 [mm] was installed vertically on the centerplane of the tunnel. A Phase Doppler Anemometer (PDA) made by Dantec (see Saffman, Buchhave and Tanger [1984]) was used to simultaneously measure the mean fluid velocity, turbulent fluctuations and bubble number density distribution. This instrument utilizes an Argon-ion laser and was mounted on the LTWT as shown in figure 2. The transmitting optics are mounted horizontally and focused on the centerplane of the tunnel. The receiving optics collect light scattered at an angle of 87° to the incident beams. The processing program of the PDA used a validation level of -4 [dB] and a band width of 4 [Hz]. It was adjusted to focus on nuclei in the diameter range of 5 [μm] to 100 [μm].

Most of the results reported here were obtained at two tunnel operation conditions, namely tunnel velocities, U , of 3.1 and 5.2 [m/sec], at a pressure of 40 [kPa]. The corresponding cavitation numbers, σ , are 7.3 and 2.8, respectively. By varying the velocity and pressure it was established that cavitation inception occurred about $\sigma \approx 2.9$ so that the flow at 3.1 [m/sec] was non-cavitating while that at 5.2 [m/sec] exhibited very limited cavitation.

Measurements of the mean velocity, turbulent fluctuations and nuclei number distributions were made at a series of locations on the centerline, namely at a point 15 diameters upstream and at locations 5, 10 and 15 diameters downstream (X/D=-15, 5, 10 and 15). Here X is the axial coordinate; the coordinate perpendicular to X and the axis of the cylinder is Y. A second series of measurements was conducted to explore the variations with Y/D.

The population dynamics of cavitation nuclei in a water tunnel are not well understood. Because of the difficulties of making reliable measurements there have been very few efforts to understand how the nuclei population in a water tunnel change with time, or with pressure, velocity and air content. A notable exception were the efforts of Keller (1972, 1974). However many questions remain. Concurrently with the present tests and effort is being made to study the nuclei population in the LTWT using the PDA. These studies will be reported later. In the present context it is however important to report that the nuclei population can change with time when the tunnel is run for an extended period of time of the order of hours. This was a concern in conducting the present experiments. However several centerline nuclei populations (at X/D=5) were repeated both before and after a series of measurements and showed relatively little discrepancy. We therefore believe that any temporal drift in the nuclei population in the present experiments was fairly small and does not alter the qualitative conclusions.

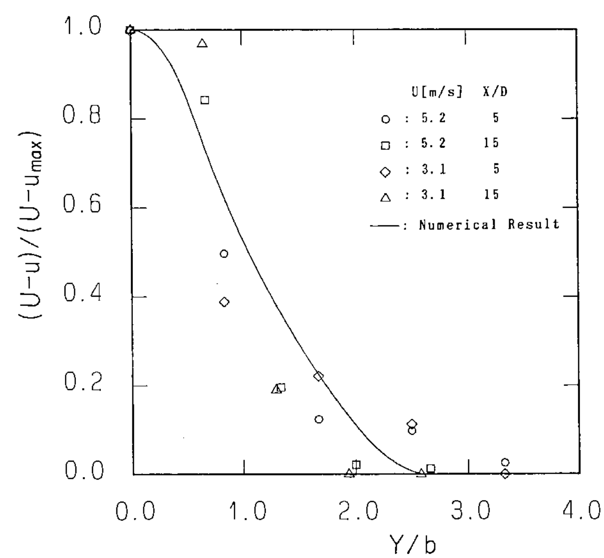

Figure 3 Mean velocity deficit in the wake. (P=40 [kPa]).

3. RESULTS AND DISCUSSION

We begin by showing in figure 3 the mean velocity deficit in the wake of the circular cylinder under the condition of P=40 [kPa]. The parameter, b, used in this figure is defined as the half width of the mean velocity deficit. It should be noted that in the case of U=5.2 [m/s], the cavitation could be observed by the human eye. On the other hand, no cavitation could be observed visually

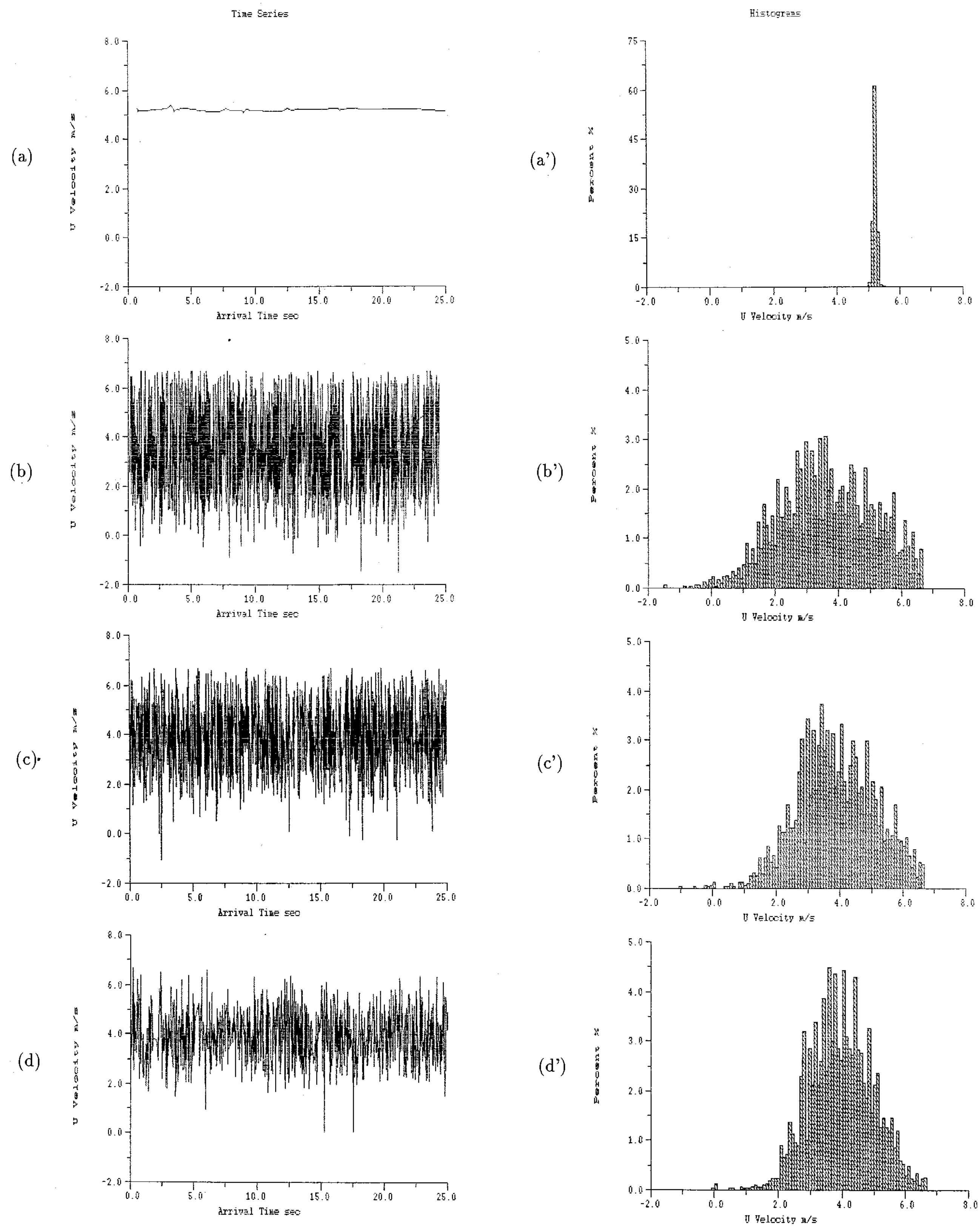

Figure 4 Oscillations and histograms in the velocity on the centerline. (U=5.2[m/s] ; P=40[kPa]).

(a), (a') : X/D=-15 ; (b), (b') : X/D=5 ; (c), (c') : X/D=10 ; (d), (d') : X/D=15.

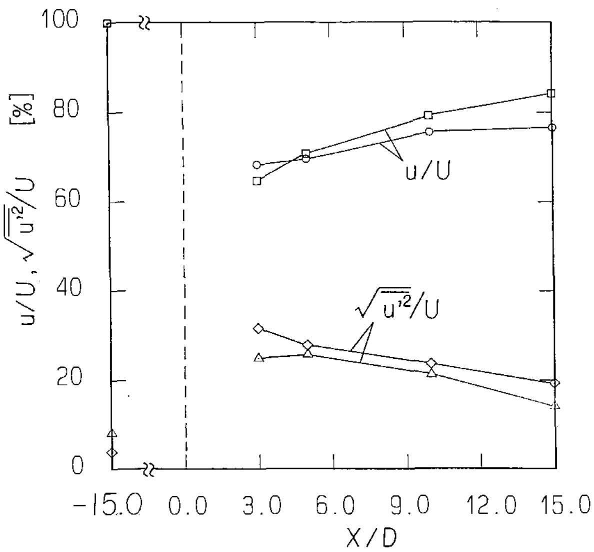

Figure 5 Variation in u/U and $(\overline{u'^2})^{\frac{1}{2}}$ / U with distance downstream along the centerline. (P=40[kPa]).
○ , ◇ : U=5.2[m/s] ; □ , △ : U=3.1[m/s].

at U=3.1 [m/s]. Clearly the influence of cavitation on the mean velocity deficit is small. In this and other later figures we shall include numerical predictions obtained using a two-dimensional discrete vortex method in which the time step was 0.1 and the separation angle was assumed to be 84°.

Typical oscillations in the velocity in the X direction, u, measured on the centerline, are shown in figure 4 for U=5.2 [m/sec], P=40 [kPa], and various X/D. Clearly the turbulence level is largest at the location X/D=5 and declines with the distance downstream; the level of turbulence in the free stream is less than 8 % . The corresponding histograms of the nuclei velocities are also shown in figure 4. Clearly the turbulence in the wake has created a distribution in the nuclei velocity but this distribution begins to narrow as one proceeds further downstream.

The variation in u/U and $(\overline{u'^2})^{\frac{1}{2}}$ / U with distance downstream along the centerline is shown in figure 5, which shows similar trends at both the U=3.1 and U=5.2 [m/sec] speeds and indicates that the level of cavitation at U=5.2 [m/sec] had little effect on the basic features of the flow. The variation in $(\overline{u'^2})^{\frac{1}{2}}$ / U with Y/D is shown in figure 6 which also includes the numerical prediction by means of the discrete vortex method. In the same figure we

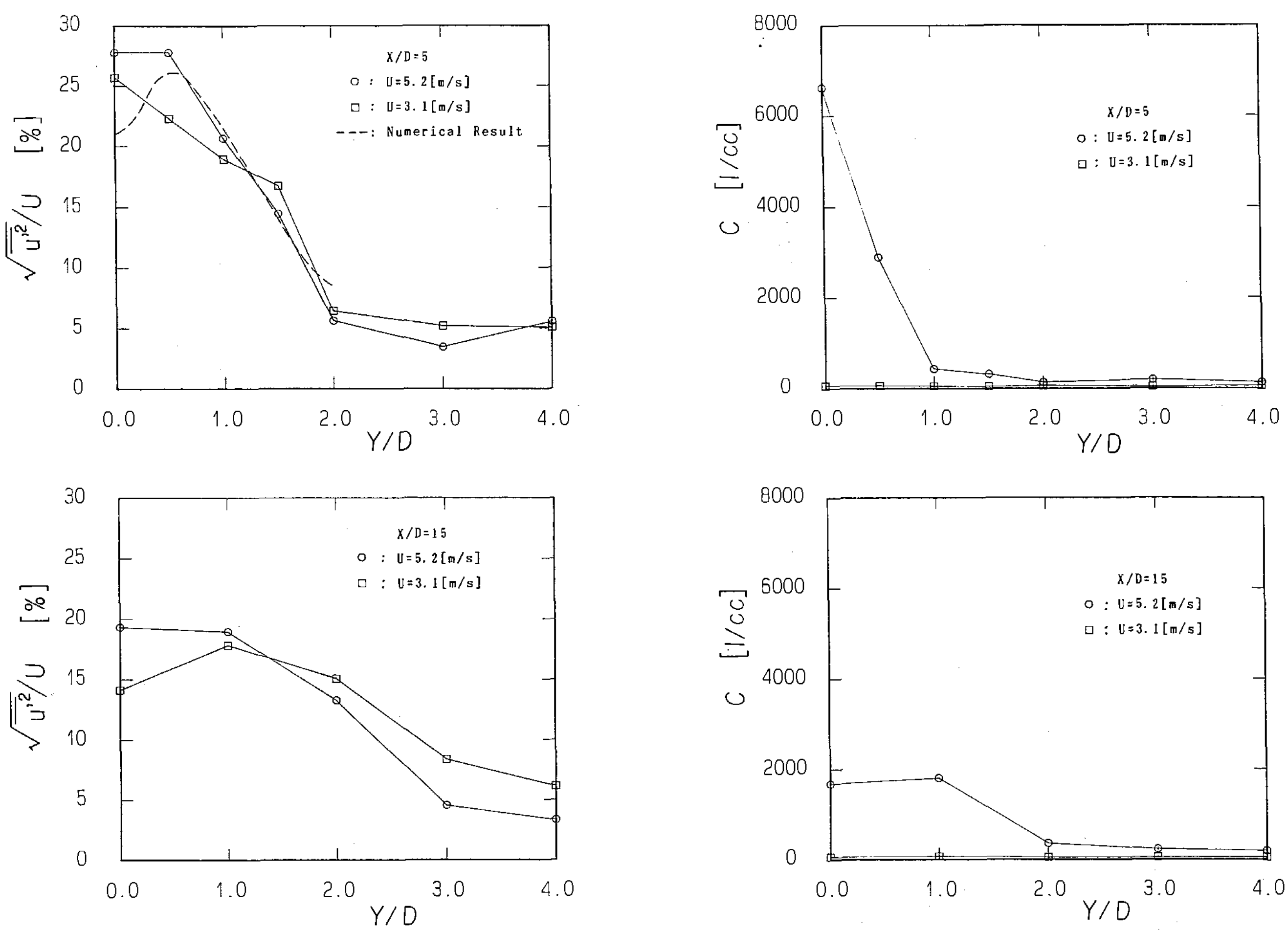

Figure 6 Variation in $(\overline{u'^2})^{\frac{1}{2}}/U$ and concentration with Y/D. (P=40[kPa]).

show the variations in the total nuclei concentration. In the latter graphs it is very clear that the cavitation occurring at U=5.2 [m/sec] has caused a major increase in the bubble population in the wake (at X/D=5) but that turbulent mixing with the free stream has substantially diluted this concentration of nuclei by X/D=15.

The lateral and longitudinal variations in the nuclei population are illustrated in figure 7 in which the volume fraction of the bubbles (calculated from the nuclei number density distribution) is plotted against Y/D (for X/D=5 and 15) and against X/D (for Y/D=0). The data for U=3.1 [m/sec] clearly exhibits a uniform population with a void fraction of about 0.0005 % throughout the flow field. On the other hand, the cavitation at U=5.2 [m/sec] has substantially increased the void fraction in the wake and one can see the effects of dilution further downstream in the wake. The right-hand graph of figure 7 also includes some data at U=5.54 [m/sec] and P=40 [kPa] or a cavitation number, σ , of 2.45 and the decrease in σ from 3.0 to 2.45 clearly can be seen to cause a more than fourfold increase in the volume fraction of the bubbles.

Having examined some global measures of the bubble population (concentration and volume fraction) we now turn to the size distribution of the nuclei/bubbles. Typical distribution are shown in figures 8,9 and 10 where $N(R)$ is plotted against the radius R in μm. Figures 8 and 9 present bubble size distributions in the centerline with and without cavitation. Figure 9 is obtained without cavitation and exhibits only small changes in the nuclei distribution. However there does appears to be a higher population of small bubbles in the wake than upstream which may be the result of a tendency for nuclei to accumulate in the wake. However, as illustrated in figure 8, the onset of very limited cavitation causes major changes which overwhelm any of the differences in figure 9. Note that there is a major increase in the number of nuclei over the entire range of radii and that figure 9 shows the same tendency for dilution with distance downstream of the cylinder. It is also important to observe that the cavitation supplies a larger increase in the number of smaller nuclei so that the slope of the $N(R)$ distribution in the wake is significantly larger than that in the upstream flow. Indeed the slope of the wake nuclei distributions is more characteristic of the $N(R)$ observed in water tunnels at higher speeds having a behavior like $N(R) \approx R^{-n}$ where n=2.5 $\rightarrow$ 3. In contrast the low speed nuclei upstream of the cylinder in the present tests have $n \approx 1$ or less. Other tests (Liu [1992]) have shown that allowing the LTWT to run under de-aerated conditions for a long period tends to cause the value of n to decrease.

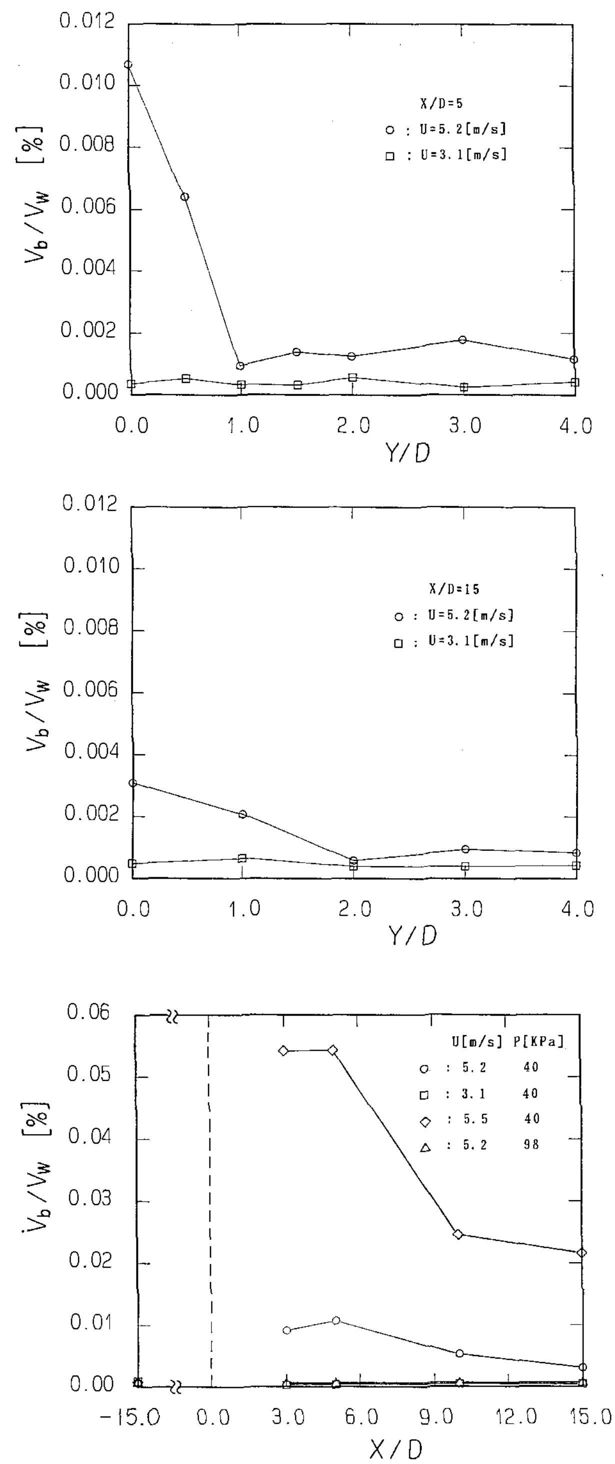

Figure 7 Volume fraction of bubbles against Y/D and X/D.

4. CONCLUSIONS

Bubble nuclei populations in the wake of a circular cylinder under cavitating and noncavitating conditions have been measured using Phase Doppler Anemometry (PDA) system to make sure the interaction between the nuclei distributions and a circular cylinder or the turbulence. It has been shown that the population in the wake with cavitation is several orders of magnitude larger than the population density upstream. Although at fifteen diameters downstream the population is still much larger than in the upstream, it declines again as nuclei are entrained into the wake.

ACKNOWLEDGEMENTS

The authors wish to thank Professor Allan Acosta for helpful advice. This work was carried out with the support of the Office of Naval Research under Grant N00014-91-J-1295.

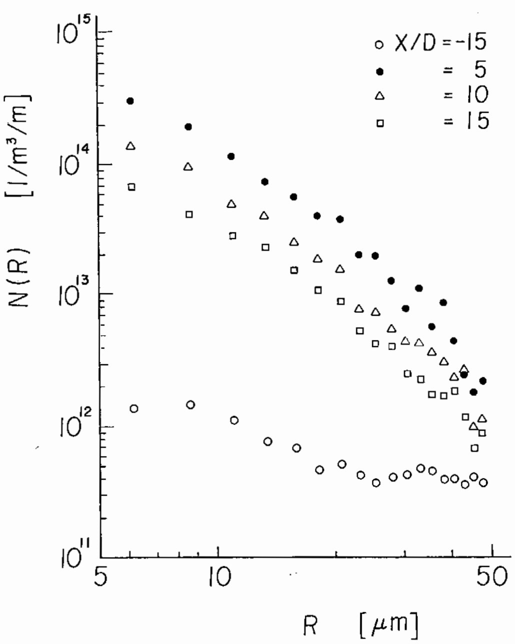

Figure 8 Bubble size distributions on the centerline with cavitation.
(U=5.2[m/s] ; P=40[kPa]).

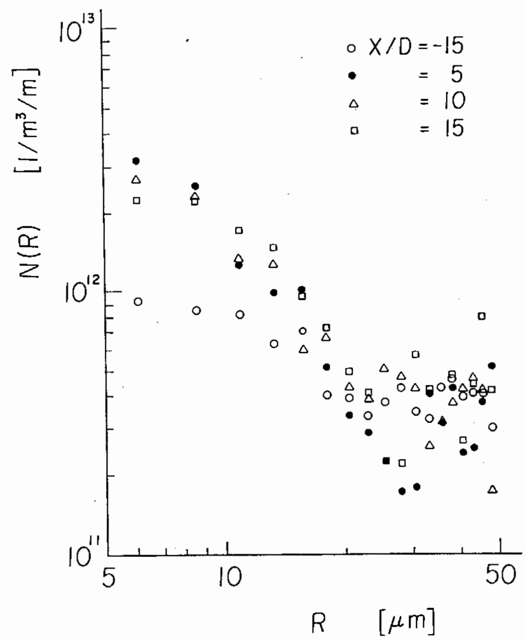

Figure 9 Bubble size distributions on the centerline without cavitation.
(U=5.2[m/s] ; P=98[kPa]).

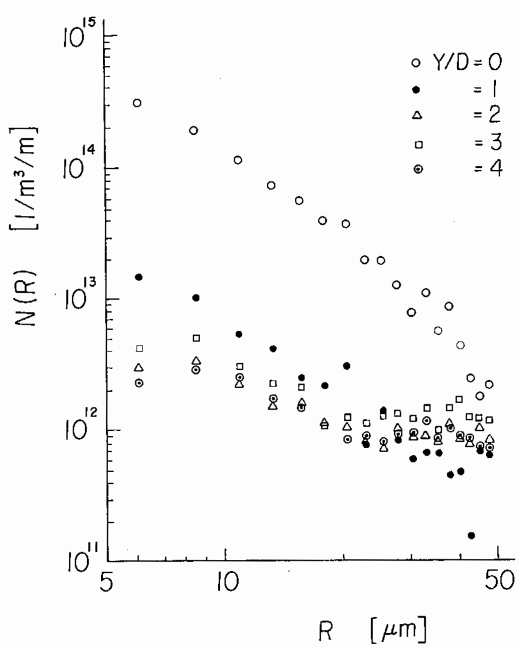

Figure 10 Bubble size distributions at X/D=5 with cavitation.
(U=5.2[m/s] ; P=40[kPa]).

REFERENCE

Acosta, A.J., O'Hern, T. and Katz, J. 1986. "Some Recent Trends in Cavitation Research," Intl. Symp. Cavitation, Sendai, Vol.1, pp. 1-7.

Ahamed, O. and Hammitt, F. G. 1975. "Determination of Particle Population Spectra from Water Tunnel Using Coulter Counter," The Univ. of Michigan, Report No.01357-4-I.

Billet, M. L. 1985. "Cavitation Nuclei Measurement - A Review," ASME Cavitation and Multiphase Flow Forum Booklet, pp. 31-38.

Ceccio, S. L. and Brennen, C. E. 1991. "Observations of the Dynamics and Acoustics of Travelling Bubble Cavitation," J. Fluid Mech., Vol.233, pp. 633-660.

Gates, E. M. 1977. "The Influence of Freestream Turbulence, Freestream Nuclei Popnlation, and Drag Reducing Polymer on Cavitation Inception on Two Axisymmetric Bodies," Calif. Inst. of Tech., Division of Engineering and Applied Science, Report E182-2.

Gates, E. M. and Bacon, J. 1978. "A Note of the Determination of Cavitation Nnclei Distributions by Holography," J. Ship Research, Vol.22, No.1, pp. 29-31.

Kato, H. 1985. "On the Structure of Cavity - New Insight into the Cavity Flow: A Summary of the Keynote Speech," Jets and Cavities Intl. Symp., ASME, FED-Vol.31, pp. 13-19.

Keller, A. P. 1972. " The Influence of the Cavitation Nucleus Spectrum on Cavitation Inception, Investigated with a Scattered Light Counting Method," ASME J. Basic Eng., Dec. 1972, pp. 917-925.

Keller, A. P. 1974. "Investigations Concerning Scale Effects of the Inception of Cavitation," Proc. Conf. on Cavitation, Inst. Mech. Eng., pp. 109-117.

Knapp, R. T., Daily, J. W. and Hammitt, F. G. 1970. "Cavitation," McGraw-Hill, Inc.

Lindgren, H. and Johnsson, C. A. 1966. "Cavitation Inception on Headforms: I.T.T.C. Comparative Experiments," Eleventh Intl. Towing Tank Conf., Tokyo.

Liu, Z. 1992. Ph.D.research in progress, Calif. Inst. of Tech.

O'Hern, T. J., d'Agostino, L. and Acosta, A.J. 1988. "Comparison of Holographic and Coulter Counter Measurements of Cavitation Nuclei in the Ocian," J. Fluids Eng., ASME, Vol.110, pp. 200-207.

Peterson, F. B., Danel, F., Keller, A. and Lecoffre, Y. 1975. "Comparative Measurements of Bubble and Particulate Spectra by Three Optical Methods," 14th Intl. Towing Tank Conf., Report of Cavitation Committee, Appendix 1.

Saffman, M., Buchhave, P. and Tanger, H. 1984. "Simultaneous Measurements of Size, Concentration and Velocity of Spherical particles by a Laser Doppler Method," Proc. 2nd Intl. Symp. on Applications of Laser Anamometry to Fluid Mechanics.